Draft

Evaluation of ionization produced by fast neutrons in Atlas muon detectors.

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1 Neutron energy spectrum and probability of interaction

The aim of this work is to estimate the ionization produced in muon detectors by fast neutrons (energy region .1 - 100 MeV). For this purpose four muon detectors were considered:

1. TGC, gas - 0.55CO_2+0.45 n-pentan (C_5H_{12})
2. RPC, gas - tetrafluoretane ($C_2H_2F_4$)
3. CSC, gas - 0.6Ar+0.3CO_2+0.1CF_4
4. MDT, gas - 0.95Ar+0.05CO_2, pressure - 3 atm.

The neutron energy spectrum was parametrised following the work of A.Ferrari ($\sim 1/E$ up to 100 MeV) and normalised on the rate of neutrons with $E > 100keV$ calculated by M.Shupe. (Jul01 Baseline, rates - $30.0 \cdot kHz/cm^2$ (CSC), $11.0 \cdot kHz/cm^2$ (TGC/MDT), $0.5 \cdot kHz/cm^2$ (RPC)) as [1]

$$n(E) = 0.145 \cdot R/E_n, \tag{1.1}$$

where $R(1/cm^2 \cdot sec)$ and $E_n(MeV)$ are the rate and energy of neutrons.

[1]Here and below energy E is in MeV.

Total cross section of neutron interactions in this energy region is a rather complicate function and was also parametrised. For C,O and F atoms the cross section were taken as

$$\sigma_i = \sigma_c \cdot (\frac{A_i}{A_c})^{2/3} \tag{1.2}$$

where $\sigma_c = 2.4 \cdot 10^{-24} \cdot E^{-.28}$ (cm^2), A_C and A_i are atomic weights of carbon and of the i^{th} component of gas mixture.

For hydrogen the cross section was taken as

$$\sigma_H = 4.1 \cdot 10^{-24}/E^{0.6}(cm^2)$$

For argon the cross section was taken as

If $E_n < 3MeV$ $\quad \sigma_{Ar} = 2.33 \cdot 10^{-24} \cdot E^{0.37}(cm^2)$

If $E_n > 3MeV$ $\quad \sigma_{Ar} = 4.76 \cdot 10^{-24}/E^{0.28}(cm^2)$

Probability of neutron interaction with i^{th} atom can be written as

$$W_i = p \cdot \sigma_i \cdot \omega_i \cdot L \cdot l, \tag{1.3}$$

Here $(p \cdot \omega_i \cdot L)$ is the number of i^{th} atom per volume unit, $L = 2.69 \cdot 10^{19}$ is Loshmidt constant for ideal gases under normal conditions, p is pressure in atm., l is average neutron path in the detector (for CSC $l = 1cm$, for MDT - $l = 3cm$), ω_i is the partial number of i^{th} atoms in the gas mixture:

$$\omega_i = \sum_{j=1}^{k} \beta_j \cdot m_{ji} \tag{1.4}$$

where β_j is the fraction of molecule j in gas mixture, m_{ji} is number of atoms i in molecule j.

For instance for a gas mixture of $0.6Ar+0.3CO_2+0.1CF_4$ used in the CSC, $\omega_C = 0.3+0.1 = 0.4$, $\omega_O = 2 \cdot 0.3 = 0.6$, $\omega_F = 0.4$ and $\omega_{Ar} = 0.6$.

Putting all those numbers together the probability of interactions(detector sensitivity) for neutrons with energy 1MeV may be obtained:

For TGC - $5.4 \cdot 10^{-4}$, for RPC - $2.8 \cdot 10^{-4}$, for CSC - $1.4 \cdot 10^{-4}$ and for MDT - $6.3 \cdot 10^{-4}$.

To compare the neutron sensitivity of different muon detectors the Fig.1 shows the dependence of probability of interactions on neutron energy.

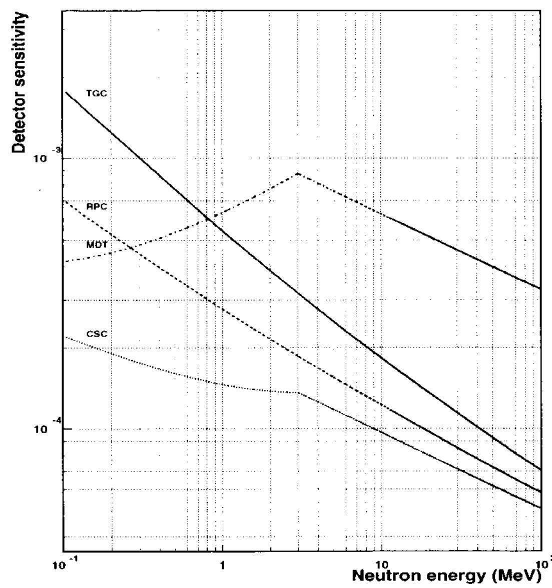

Figure 1: Sensitivity of muon detectors versus neutron energy

Combining together the neutron spectrum and the interaction probabilities we can get the dependence of rate of neutron interactions on energy.

$$N_i(E) = n(E) \cdot W_i \tag{1.5}$$

	$N_H = N_H(1MeV)/E^{1.6}$
For C,O or F atoms	$N_i(E) = N_i(1MeV)/E^{1.28}$
if $E_n < 3MeV$	$N_{Ar} = N_{Ar}(1MeV)/E^{0.63}$
if $E_n > 3MeV$	$N_{Ar} = N_{Ar}(1MeV)/E^{1.28}$

where $N_i(1MeV)$ is the number of interactions a $1MeV$ neutrons with i^{th} atom of gas mixture.

2 Energy distribution of the recoil nuclei

In the considered energy region the main contribution to the total cross-section comes from neutron elastic scattering on a nucleus. In an elastic collision the energy of recoil nucleus has a flat distribution from 0 to $\alpha_i \cdot E_n$, where E_n is neutron kinetic energy, $\alpha_i = 4 \cdot A_i/(1+Ai)^2$, A_i is the i^{th} atom mass. For a given neutron energy the nucleus recoil energy of E_r is distributed as

$$P_i(E_r) \cdot dE_r = \frac{dE_r}{\alpha_i \cdot E_n} \tag{2.1}$$

The energy spectrum of recoil nuclei can be obtained by integrating over neutron energies as show below:

If $E_r \leq \alpha \cdot E_{min}$

$$P_i(E_r) = \frac{1}{\alpha_i} \int_{E_{min}}^{E^{max}} N_i(E_n) \frac{dE_n}{E_n} \tag{2.2}$$

If $E_r > \alpha \cdot E_{min}$

$$P_i(E_r) = \frac{1}{\alpha_i} \int_{E_r/\alpha_i}^{E^{max}} N_i(E_n) \frac{dE_n}{E_n}$$

For example, for C,O and F atoms the recoil energy spectrum is

If $E_r \leq \alpha \cdot E_{min}$

$$P_i(E_r) = \frac{N_i(1MeV)}{1.28 \cdot \alpha_i} \cdot (1/E_{min}^{1.28} - 1/E_{max}^{1.28})$$

If $E_r > \alpha \cdot E_{min}$

$$P_i(E_r) = \frac{N_i(1MeV)}{1.28 \cdot \alpha_i} \cdot ((\alpha_i/E_r)^{1.28} - (1/E_{max})^{1.28})$$

Here E_r is the kinetic energy of recoil nucleus, $E_{min} = .1MeV, E_{max} = 1MeV$ are lower and upper boundaries of the neutron energy spectrum, $N_i(1MeV)$ is the number of interaction of neutron at $1MeV$.

Fig.2 shows the recoil nuclei energy spectrum for components of the CSC gas mixture.

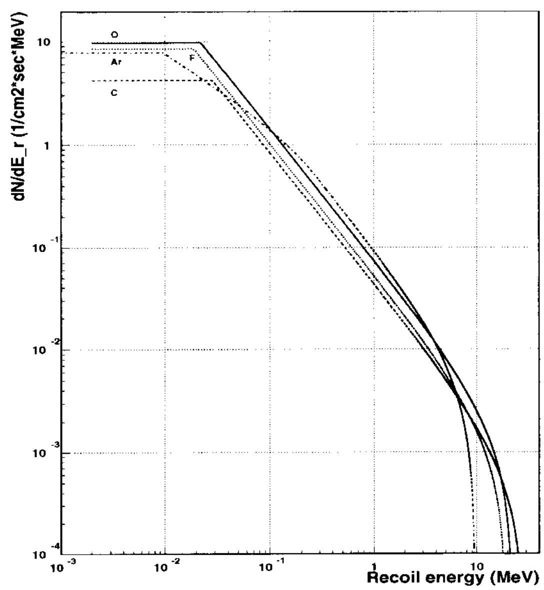

Figure 2: Energy spectrum of recoil nuclei in CSC

3 Energy of recoil nucleus transfered to ionization

The the recoil nucleus transfer to ionization in the detector only part its kinetic energy. There are two reasons of this. First, at a high kinetic energy the nucleus range may be bigger than the detector gas gap. In this case a part of energy of nucleus escapes from sensitive volume. Let us estimate the value of energy when the range of nucleus is equal the average distance from an interaction point to the detector walls. From nuclear photo-emulsion measurements ($< Z > \approx 40$) the kinetic energy of a nucleus with mass A and its range are related according to the formula:

$$E_A = g \cdot (A)^{1-n} \cdot R^n \tag{3.1}$$

where $g = 0.143$, $n = 0.58$, R in mg/cm^2, E in MeV.

Taken into account dependence of stopping power of the media on its atomic number ($< Z >$ of the gas mixture is 3.3, 6.3, 10.8 and 16.6 for TGC,RPC,CSC and MDT), this energy should be increased by factor 2.8, 2.2, 1.7 and 1.5 for TGC, RPC, CSC and MDT correspondingly. Table 1 shows the minimal kinetic energy E_{escp} when nucleus range becomes equil half of average neutron path in detector sensitive volume.

Table 1 The value $E_{escp}(MeV)$ for components of detectors gas mixture

Detector	Gas gap (mg/cm^2)	H	C	O	F	Ar
TGC	0.81	0.35	1.0	1.14		
RPC	0.91	0.3	0.85		1.0	
CSC	1.		0.69	0.78	.84	1.14
MDT	16.		3.1	3.4		5.1

For simplicity we will suppose that the nucleus with energy above the values shown in table 1 will deposit in the detector exactly E_{escp}.

Another reason of the ionization power reduction is connected with low velocity of recoil nuclei. At low velocities significant part of kinetic energy of nucleus dissipates in the gas other way than ionization (mostly through atomic collisions). Therefore electron ionization fraction drops fast when energy becomes less than some value. This phenomenon is described in details in the Atlas muon note published by Boston University group [1]. We will use some formulas from this note.

Following this work we introduce a unit-less ionization energy ϵ

$$\epsilon = b \cdot E_r \tag{3.2}$$

Here $E_r(MeV)$ is kinetic energy of nucleus. Coefficient b depends on atomic number Z and atomic mass A both recoil nucleus and gas media.

$$b = \frac{19.5 \cdot 10^3 \cdot A_2}{Z_1 \cdot Z_2 \cdot (Z_1^{2/3} + Z_2^{2/3})^{1/2} \cdot (A_1 + A_2)} \tag{3.3}$$

where Z_1, A_1 are atomic number and mass of recoil nucleus, Z_2, A_2 average atomic number and mass of media

The calculated coefficients b for all muon detectors are presented in Table 2.

Table 2 Coefficients $b(1/MeV)$ for the components of detectors gas mixture

Detector	H	C	O	F	Ar
TGC	2830	220	130		
RPC	1381	103		50	
CSC		69.	44.6	36.2	10.7
MDT		47.4	31.7		8.6

Dependence of the ionization fraction $\xi = E_{ion}/E_r$ on the unit-less energy ϵ is presented in the note [1]. For our calculations this dependence was parametrised in the following way:

- if $\epsilon < 128$ $\qquad \xi = 0.46 \cdot \epsilon^{0.16}$

- if $\epsilon > 128$ $\qquad \xi = 1$

When the value of ϵ exceeds 128 the ionization processes go usual way and a deposited energy produces the expected value of ionization charge. The value of energy $E_r^* = 128/b$, where the proportionality between deposited energy and charge is violated, strong depends on atomic number of both the recoil nucleus and the stopping media. For-instance for H in TGC E_r^* is $0.05(MeV)$, for C and Ar in CSC are $1.9(MeV)$ and $12.(MeV)$ correspondingly. As one may see the effect of reducing of ionization is practically negligible for recoil protons. On the other hand in case of nucleus of Ar this effect covers all recoil energy spectrum (Ar maximal recoil energy is 9.5 MeV).

To calculate the ionization deposited in the detector it is necessary in recoil energy spectrum to change a variable E_r and dE_r on E_{ion} and dE_{ion}

$$E_{ion} = \xi \cdot E_r = 0.46 \cdot (b \cdot E_r)^{0.16} \cdot E_r = 0.46 \cdot b^{0.16} \cdot E_r^{1.16} \tag{3.4}$$

It is easy to show

$$E_r = \frac{1.95}{b^{0.138}} \cdot E_{ion}^{0.862} \qquad and \qquad dE_r = \frac{1.68}{(b \cdot E_{ion})^{0.138}} \cdot dE_{ion} \tag{3.5}$$

Now we can write the spectrum of the ionization energy, deposited in the detector. For atoms C,O and F the spectrum is following:

if $E_r < \alpha \cdot E_{min}$

$$P_{ion}^i \cdot dE_{ion} = \frac{1.31 \cdot N_i(1MeV)}{\alpha_i \cdot (b_i \cdot E_{ion})^{0.138}} \cdot [(1/E_{min})^{1.28} - (1/E_{max})^{1.28}]dE_{ion} \tag{3.6}$$

if $E_r > \alpha \cdot E_{min}$

$$P_{ion}^i \cdot dE_{ion} = \frac{1.31 \cdot N_i(1MeV)}{\alpha_i \cdot (b_i \cdot E_{ion})^{0.138}} \cdot [(\alpha_i/E_r)^{1.28} - (1/E_{max})^{1.28}] \cdot dE_{ion} \tag{3.7}$$

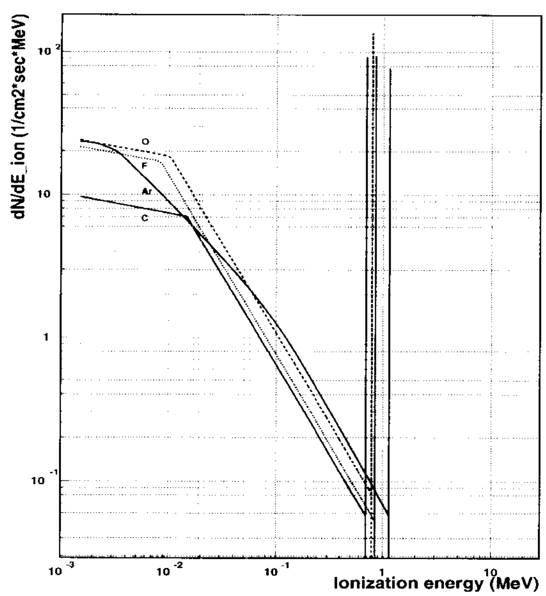

Figure 3: Spectrum of ionization deposition of neutrons in CSC

For CSC the spectrum of ionization energy is shown in the fig.3. Peaks on the end of the spectrum correspond to ionization energy deposited by the recoil nuclei with ranges exceeding detector gas depth. The integral over the spectrum is the total ionization energy deposited by neutrons in the detector per $cm^2 \cdot sec$

As example some results of calculations for different component of CSC gas mixture are shown in Table 3. The rate of neutron interactions, the total energy transfered by neutrons to recoil nuclei $\int E_r$, the total ionization energy $\int E_{ion}$ deposited in detector, the average recoil energy $< E_r >$ and average ionization deposition per one interaction $< E_{ion} >$ are presented in this table.

Table 3 Neutron energy deposition in CSC.

Atom	C	O	F	Ar	Total
$Rate(1/cm^2 \cdot sec)$	0.66	1.19	0.88	1.02	3.75
$\int E_r$, $(MeV/cm^2 \cdot sec)$	0.6	0.86	0.55	0.59	2.6
$\int E_{ion}$, $(MeV/cm^2 \cdot sec)$	0.13	0.22	0.17	0.27	0.79
$< E_r >$, (MeV)	0.93	0.72	0.62	0.57	0.7
$< E_{ion} >$, (MeV)	.2	.19	.185	.26	0.21

The relative contributions of each component to total ionization energy $\int E_{ion}$ in different detectors are presented in Table 4. The sum of all components for given detector is equal unit.

Table 4 The relative contribution of different gas components to total ionization.

Detector	H	C	O	F	Ar
TGC	0.61	0.27	0.12		
RPC	0.27	0.21		0.52	
CSC		0.17	0.29	0.21	0.33
MDT		0.05	0.11		0.84

It is interesting to compare the total ionization energy deposited by neutrons and by photons associated with the same neutron flux. The ionization energy deposited by neutrons $\int E_n^{ion}$ and gamma $\int E_\gamma$ and their ration are presented in Table 5. To calculate $\int E_\gamma$ it is needed to know γ flux which depends on detector position, sensitivity detectors to γ interactions and average deposited energy in one interaction. The values of fluxes were taken from Shupe's background calculations (Jul01 Baseline) for following detector positions:

TGC $\overline{Z}$=720cm., $\overline{R}$=270cm.

MDT $\overline{Z}$=720cm., $\overline{R}$=270cm.

CSC $\overline{Z}$=740cm., $\overline{R}$=150cm.

RPC Z=200-400cm., R=510cm. (Inner Barrel - Mid Z)

The γ sensitivity all considering detectors was taken $6 \cdot 10^{-3}$ (we suppose that most of electrons enter into detector sensitive volume from the walls). The average ionization energy deposited by high momentum muon, γ and neutron is presented in the same table also. For muon dE/dx relativistic rise was taken into account (factor 1.5)

Table 5

Detector	TGC	RPC	CSC	MDT
$< E_n >_{ion}$, (MeV)	0.22	0.21	0.18	0.25
$< E_\gamma >$, (MeV)	.0065	.0073	.008	.036
$< E_{muon} >$, (MeV)	.0016	.0018	.002	.024
$\int E_n^{ion}$, $(MeV/cm^2 \cdot sec)$	1.31	0.054	0.79	2.95
$\int E_\gamma$, $(MeV/cm^2 \cdot sec)$	0.45	0.054	1.32	2.46
$\int E_n^{ion} / \int E_\gamma$	2.93	1.	0.6	1.2

4 Conclusion

As was shown above the fast background neutrons contribute significant ionization in Atlas muon detectors. The calculated ionization is the ionization charge before electron multiplication. How this ionization can contribute to the total accumulated charge after multiplication? Generally say two scenarios are possible. The recoil nuclei have high ionization density and therefore local space charge may reduce electron multiplication especially at high gas gain. In this case the effect of neutrons ionization will be significantly smaller. In the other hand high density ionization may initialise the strimer. In this case the neutron contribution to the total accumulated charge may be even more significant.

All presented calculations of neutron interactions do not include the ionization of the recoil nuclei penetrating from the walls. However at high kinetic energy the range of the recoil nuclei may be the same as the detector gas gap. From our calculations the fraction of the recoil nuclei with energies exceeded E_{escp} for most muon detectors (except MDT) is about 20 percents. This value can be taken as rough estimation of the walls contribution in detectors with thin gap (TGC, RPC, CSC). For MDT this fraction contains about one percent only. So for MDT this effect it seems to be rather small.

In order to make more certain conclusions concerning the neutron ionization ~~by neutron~~ the special study the detectors respond to fast neutrons are needed. As the first approximation it will be useful to check the respond muon detectors to α-particles. The α-particles may imitate the single charge recoil nuclei very good. Indeed, owing to its double charge α-particle produces the same ionization density as nucleus of oxygen with the same kinetic energy.

5 References

1. S. Ahlen et al., Atlas note ATL-MUON-NO-236 13 May, 1998
2. A.S. Denisov et al Preprint 1941, Gatchina, 1993
3. A.Gordeev et al., Atlas note ATL-MUON-2000-005 (ATL-COM-MUON-99-032)
4. Mario Deile, Dissertation